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VFT Application for Asynchronous Power Transfer

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***Abstract*—The variable frequency transformer (VFT) developed recently is a flexible asynchronous ac link which is used to transfer power in-between asynchronous power system networks. The first VFT was installed at the Langlois substation, which interconnects the New York (USA) and the Hydro-Québec (Canada) systems. Basically, it is a rotary transformer whose torque is externally adjusted in order to control the power transfer. In the paper, a simulated model of VFT is present, which is used as a controllable bidirectional power transmission device that can control power transfer through the asynchronous power system networks. A digital simulation model of VFT and its control system are developed with MATLAB Simulink and a series of studies on power transfer through asynchronous power system networks are carried out with this model. Moreover, the response characteristics of power transfer under various torque conditions are discussed. Further voltage, current, torque and power transfer plots are also obtained. Thus, the VFT concept and its advantages are verified by simulation results.**

***Index Terms*—Variable Frequency Transformer (VFT), Flexible asynchronous ac link, MATLAB Simulink, Power System networks, Power transfer.**

I. Introduction

The world's electric power supply systems are widely interconnected, involving connections inside utilities' own territories which extend to inter-utility interconnections and then to inter-regional and international connections. This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply [1]. Power flow control is an important issue in interconnected power system networks. Phase shifting transformers and back-to-back HVDC converters are typical methods used to effectively control power flow in those systems [2].

The phase shifting transformer controls real and reactive power flows by varying the voltage angle and magnitude. It is simple and economic but increases the complexity of power system operation and decreases the stabilities of the power system under some serious faults. The drawbacks of this arrangement are that the operation is stepwise (rather than continuous) and slow (to deal with stability related constraints on the grid). For this reason, the phase shifting transformer is replaced by another one known as back-to-back HVDC. The back-to-back HVDC system controls power flow by controlling the converter valve group firing angle. In back-to-back HVDC applications, the rectifier and the inverter are located in the same station and are normally used to interconnect the two asynchronous power system networks. It is easy for bulk power transfer and also flexible for system operation. But the design of HVDC system is quite complicated and expensive. The HVDC link requires a very costly converter plant at sending end and an inverter plant at receiving end. Alternatively recently, a new technology known as variable frequency transformer (VFT) has been developed for transmission interconnections [2-10]. By adding different devices with it, power transfer can be controlled in-between power system networks in a desired way [3].

II. VFT Concept and Components

A variable frequency transformer (VFT) is a controllable, bidirectional transmission device that can transfer power in-between asynchronous power system networks [4]. The construction of VFT is similar to conventional asynchronous machines, where the two separate electrical networks are connected to the stator winding and the rotor winding, respectively. One power system is connected with the rotor side of the VFT and another power system is connected with the stator side of the VFT. The electrical power is exchanged between the two networks by magnetic coupling through the air gap of the VFT and both are electrically isolated.

The VFT is essentially a continuously adjustable phase shifting transformer that can be operated at an adjustable phase angle. The VFT consists of following core components: a rotary transformer for power exchange, a drive motor to control the movement or speed of the rotor and to control the transfer of power. A drive motor is used to apply torque to the rotor of the rotary transformer and adjust the position of the rotor relative to the stator, thereby controlling the magnitude and direction of the power transmission through the VFT [5]. The world's first VFT, was manufactured by GE, installed and commissioned in Hydro-Quebec's Langlois substation, where it is used to exchange power up to 100 MW between the asynchronous power grids of Quebec (Canada) and New York (USA) [4-6].

A stable power exchange between the two asynchronous systems is possible by controlling the torque applied to the rotor, which is controlled externally by the drive motor. When the power systems are in synchronism, the rotor of VFT remains in the position in which the stator and rotor voltage are in phase with the associated systems. In order to transfer power from one system to other, the rotor of the VFT is rotated. If torque applied is in one direction, then power transmission takes place from the stator winding to the rotor winding. If torque is applied in the opposite direction, then power transmission takes place from the rotor winding to the stator winding. The power transmission is proportional to the magnitude and direction of the torque applied. The drive motor is designed to continuously produce torque even at zero speed (standstill). When the two power systems are no longer in synchronism, the rotor of the VFT will rotate continuously and the rotational speed will be proportional to

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the difference in frequency between the two power systems (grids). During this operation the power transmission or flow is maintained. The VFT is designed to continuously regulate power transmission even with drifting frequencies on both grids. Regardless of power transmission, the rotor inherently orients itself to follow the phase angle difference imposed by the two asynchronous systems [7].

III. VFT Model and Analysis

A. VFT Model

In the model, the VFT is a doubly-fed wound rotor induction machine (WRIM), the three phase windings are provided on both stator side and rotor side. The two power systems (#1 and #2) are connected through the VFT as shown in Fig. 1. The power system#1 is connected to the stator side of the VFT, energized by voltage, V_S with phase angle, θ_S. The power system#2 is connected to the rotor side of the VFT, energized by voltage, V_r with phase angle, θ_r. A drive motor is mechanically coupled to the rotor of WRIM. A drive motor and control system are used to apply torque, T_D to the rotor of the WRIM which adjusts the position of the rotor relative to the stator, thereby controlling the direction and magnitude of the power transmission through the VFT [8].

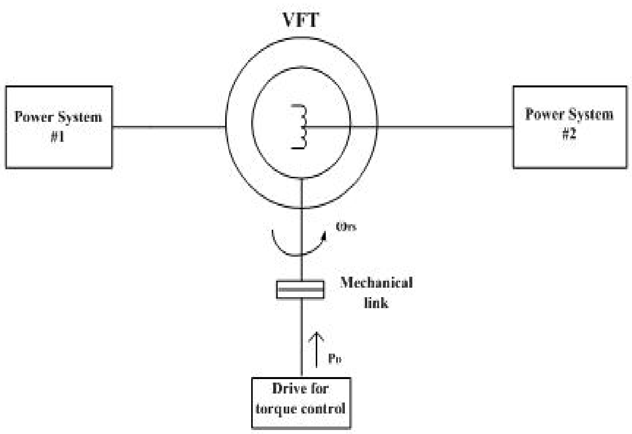

Figure 1. The VFT model representation

It is better to represent the VFT model by an equivalent VFT power transmission or power transfer model, as shown in Fig. 2. The power transfer direction shows the power transmission from power system#1 to power system#2 through VFT. In fact, the direction of power transfer could be from power system#1 to power system#2 or vice-versa depending on the operating conditions. If torque is applied in one direction then power transfer takes place from power system #1 to power system#2. If torque is applied in opposite direction then power transfer reverses as shown in Fig. 4. Here, in the power transfer process, only real power transfer is being discussed.

B. VFT Analysis

i) Power transfer from Power system#1 to Power system#2 The power transfer through the variable frequency transformer (VFT) can be approximated as follow:

$$P_{VFT} = P_{MAX} \, Sin \, \theta_{net} \tag{1}$$

where,

P_{VFT} = Power transfer through VFT from stator to rotor,

P_{MAX} = Maximum theoretical power transfer possible through the VFT in either direction which occurs when the net angle ¸ *net* is near 90Ú. The P_{MAX} is given by:

$$P_{MAX} = Vs \, Vr / X_{sr} \tag{2}$$

where,

Vs = Voltage magnitude on stator terminal,

Vr = Voltage magnitude on rotor terminal and

X_{sr} = Total reactance between stator and rotor terminals.

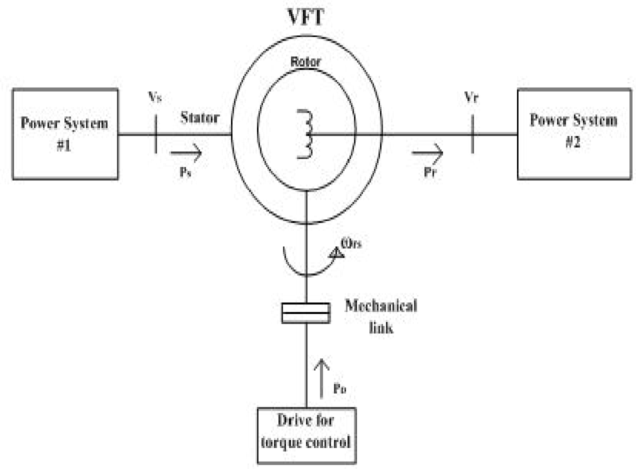

Figure 2. Power transfer from power system #1 to power system #2 using VFT

Also $$\theta_{net} = \theta_s - (\theta_r + \theta_{rs}) \tag{3}$$

where,

θ_s = Phase-angle of ac voltage on stator, with respect to a reference phasor,

θ_r= Phase-angle of ac voltage on rotor, with respect to a reference phasor and

θ_{rs} = Phase-angle of the machine rotor with respect to stator.

Thus, the power transfer through the VFT is given by:

$$P_{VFT} = ((Vs\ Vr/\ Xsr)\ sin(\theta s - (\theta r + \theta rs)) \tag{4}$$

The phasor diagram showing reference phasor, *Vs*, *Vr*, θ_s, θ_r, θ_{rs} and θ_{net} is shown in Figure 3.

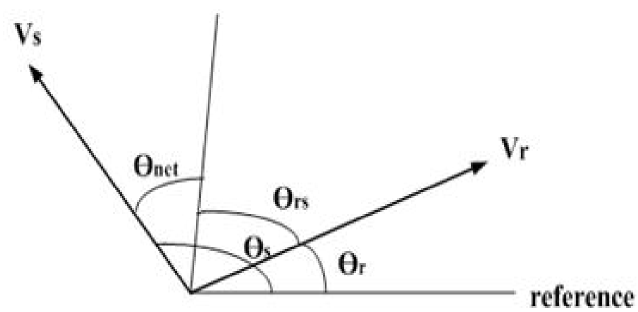

Figure 3. The phasors of VFT

For stable operation, the angle ¸net must have an absolute value significantly less than 90Ú. The power transmission or power transfer will be limited to a fraction of the maximum theoretical level given in (2). Here, the power transmis

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sion equations are analyzed based on assumption that VFT is an ideal and lossless machine, with negligible leakage reactance and magnetizing current. The power balance equation requires that the electrical power flowing out of the rotor winding must flow into the combined electrical path on the stator winding and the mechanical path to the drive system, i.e.

$$P_r = P_s + P_D \tag{5}$$

where,

P_s = electrical power to the stator windings,

P_r = electrical power out of the rotor windings and

P_D = mechanical power from the torque-control drive system.

Since the machine behaves like a transformer, mmf provided by the ampere-turns of stator must balance the rotor mmf:

$$N_s*I_s = N_r*I_r \tag{6}$$

where,

N_s = number of turns on stator winding,

N_r = number of turns on rotor winding,

I_s = current to the stator winding and

I_r = current out of the rotor winding.

Both the stator and rotor windings link the same magnetic flux but their frequency differs such that the voltage will also differs by the same ratio, therefore

$$V_s = N_s * f_s * \psi_a, \tag{7}$$

$$V_r = N_r * f_r * \psi_a, \tag{8}$$

$$\text{and } V_r / N_r = V_s / N_s * f_r / f_s \tag{9}$$

where,

f_s = frequency of voltage on stator winding (Hz),

f_r = frequency of voltage on rotor winding (Hz), and

ψ_a = air-gap flux.

The nature of the machine is such that in steady state, the rotor speed is proportional to the difference in the frequency (electrical) on the stator and rotor windings,

$$f_{rm} = fs - fr, \tag{10}$$

$$\text{and } \omega_{rm} = f_{rm} * 120 / N_P \tag{11}$$

where,

f_{rm} = rotor mechanical speed in Hz,

N_P = number of poles in the machine, and

ω_{rm} = rotor mechanical speed in rpm.

Combining the relationships gives the power exchanged with the drive system as

$$P_D = P_r - P_s = V_r*I_r - V_s*I_s$$

$$= V_r*I_r - (N_s*V_r/N_r*f_s/f_r)*(N_r*I_r/N_s)$$

$$= V_r*I_r*(1 - f_s/f_r)$$

$$\text{or, } P_D = P_r*(1 - f_s/f_r) \tag{12}$$

It shows that the electrical power flowing out of the rotor winding being proportional to mechanical power of the drive system, stator frequency and rotor frequency. Hence, if the stator frequency and rotor frequency are kept constant, then the electrical power flowing out of the rotor winding being only proportional to mechanical power of the drive system.

ii) Power transfer from Power system#2 to Power system#1

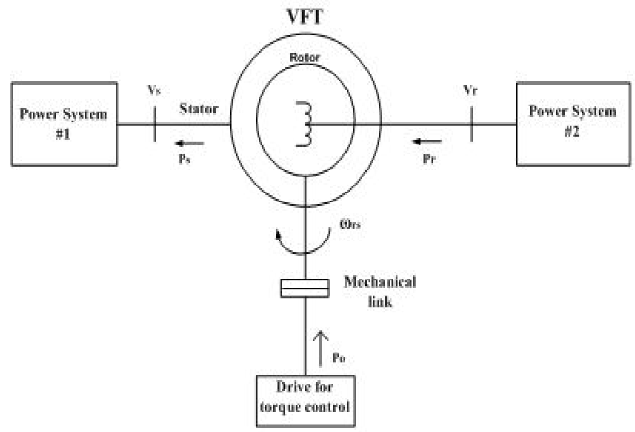

Figure 4. Power transfer from power system #2 to power system #1 using VFT

The power balance equation requires that the electrical power flowing out of the stator winding must flow into the combined electrical path on the rotor winding and the mechanical path to the drive system, i.e.

$$Ps = P_D + Pr \tag{13}$$

where,

P_s = electrical power to the stator windings,

P_r = electrical power to the rotor windings and

P_D = mechanical power from the torque-control drive system.

Since the machine behaves like a transformer, the ampere-turns must balance between stator and rotor:

$$N_s*I_s = N_r*I_r \tag{14}$$

where,

N_s = number of turns on stator winding,

N_r = number of turns on rotor winding,

I_s = current out of the stator winding and

I_r = current out of the rotor winding.

Both the stator and rotor windings link the same magnetic flux but their frequency differs such that the voltage will also differs by the same ratio, therefore

$$V_s = N_s * f_s * \psi_a, \tag{15}$$

$$V_r = N_r * f_r * \psi_a, \tag{16}$$

$$\text{and } V_r / N_r = V_s / N_s * f_r / f_s \tag{17}$$

where,

f_s = frequency of voltage on stator winding (Hz),

f_r = frequency of voltage on rotor winding (Hz), and

ψ_a = air-gap flux.

The nature of the machine is such that in steady state, the rotor speed is proportional to the difference in the frequency (electrical) on the stator and rotor windings,

$$f_{rm} = fs - fr, \tag{18}$$

$$\text{and } \omega_{rm} = f_{rm} * 120 / N_P \tag{19}$$

where,

f_{rm} = rotor mechanical speed in Hz,

N_P = number of poles in the machine, and

ω_{rm} = rotor mechanical speed in rpm.

Combining the relationships gives the power exchanged with the drive system as

$$P_D = P_s - P_r = V_s*I_s - V_r*I_r$$

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$$= V_s*I_s - (N_r*V_s/N_s*f_r/f_s)*(N_s*I_s/N_r)$$
$$= V_s*I_s*(1 - f_r/f_s)$$

$$\text{or, } P_D = P_s*(1 - f_r/f_s) \tag{20}$$

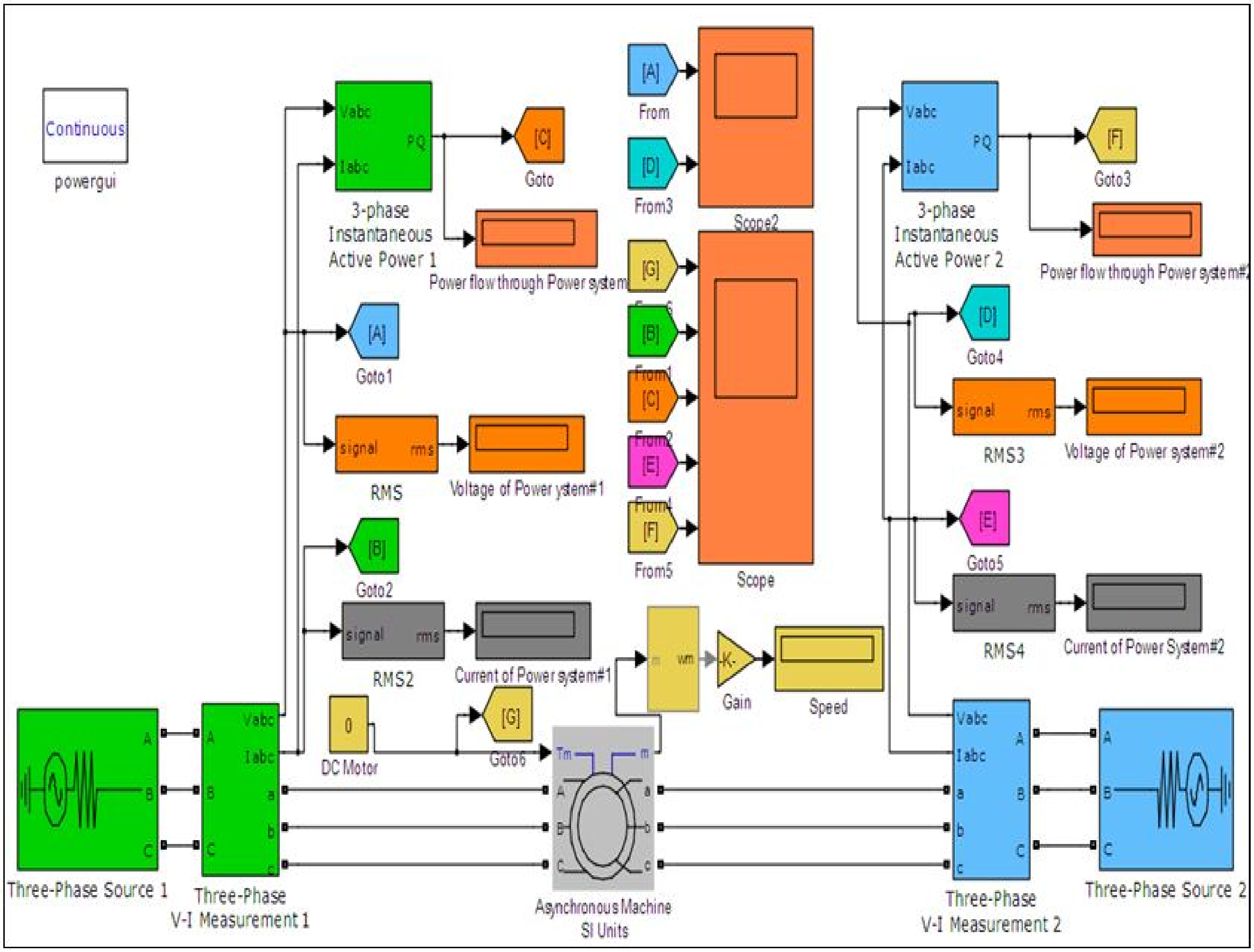

Figure 5. MATLAB Simulation model of VFT based power system networks

It shows that the electrical power flowing out of the stator winding being only proportional to mechanical power of the drive system, rotor frequency and stator frequency. Hence, if the rotor frequency and stator frequency are kept constant, then the electrical power flowing out of the stator winding being only proportional to mechanical power of the drive system.

IV. Digital Simulation of VFT

A. MATLAB Simulation Model

For MATLAB, here VFT is represented as a wound rotor induction machine (WRIM). The WRIM is doubly-fed and is simulated with the asynchronous machine SI units in MATLAB Simulink [9-10]. The power system#1 and power system#2 are simulated with three phase voltage sources as shown in Fig. 4. The three phase voltage source 1 is connected to the stator side of WRIM and the three phase voltage source 2 is connected to rotor side of WRIM. The drive motor is simulated with constant block which gives constant torque. The torque is applied to WRIM as mechanical torque T_m. To simulate various power transfer functions, other blocks are also used. The power system#1 is kept at 400V (L-L) and 60Hz whereas power system#2 is kept at 300V (L-L) and 50 Hz. Then this simulated model, as shown in Fig. 5, is used to solve electric power system using VFT.

Under different torque conditions, the power transfer through power system#1 and power system#2 is simulated. The simulated waveforms of stator voltage, rotor voltage, stator current, rotor current, speed and torque are shown in Figs. 6 – 15.

B. MATLAB Simulation Results

i) Power transfer from Power system#1 to Power system#2

It is evident from the simulated results that under different external torque condition, the power transfer through the power system#1 and power system#2 is not zero. The magnitude and frequency of voltage are kept same for all operating conditions (Fig.6) and the power transfer through power sytem#1 and power system#2 under different torque condition are shown in Figs. 7-11.

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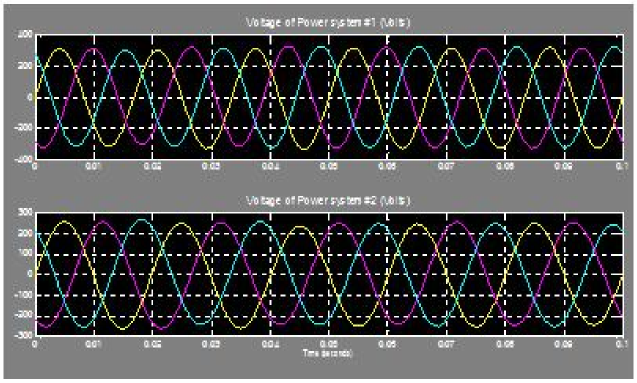

Figure 6. Voltage waveforms of stator and rotor side of VFT

a) For $T_D = 0$ Nm, Fig. 7 shows the waveforms.

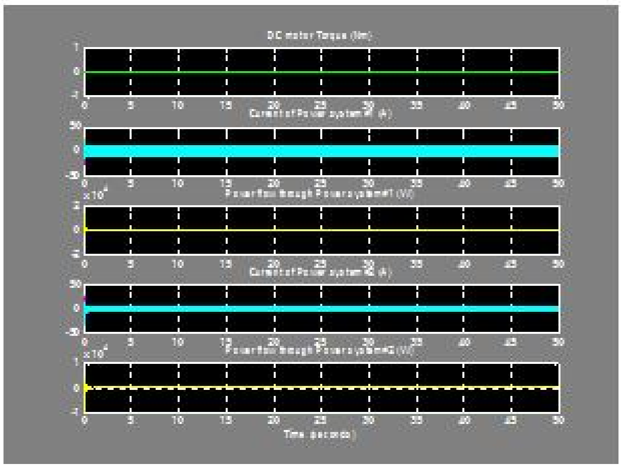

Figure 7. Waveforms showing torque, currents and power transfer

b) For $T_D = 5$ Nm, Fig.8 shows the waveforms.

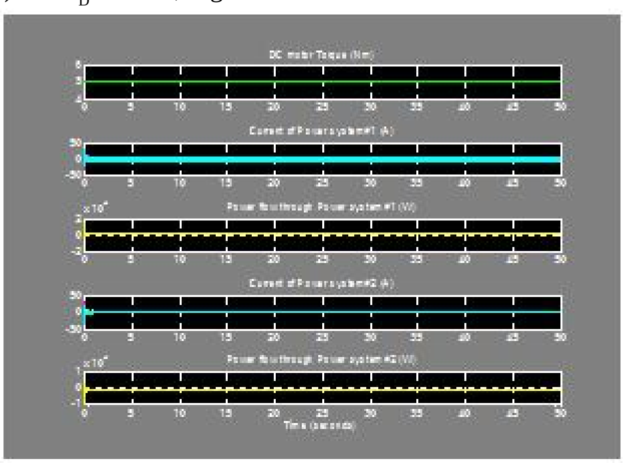

Figure 8. Waveforms showing torque, currents and power transfer

It is clear from table I that under zero torque condition the power transfer through the VFT is zero even though there is power transfer through power system#1 and power system#2 i.e. VFT is taking power from both the power systems. The negative sign represents the power transfer inside the power system#2.

ii)<u>Power transfer from Power system#1 to Power system#2</u>

When the applied torque is in opposite direction then power transfer direction reverses as shown in Figs. 12-15.

c) For $T_D = 10$ Nm, Fig.9 shows the waveforms.

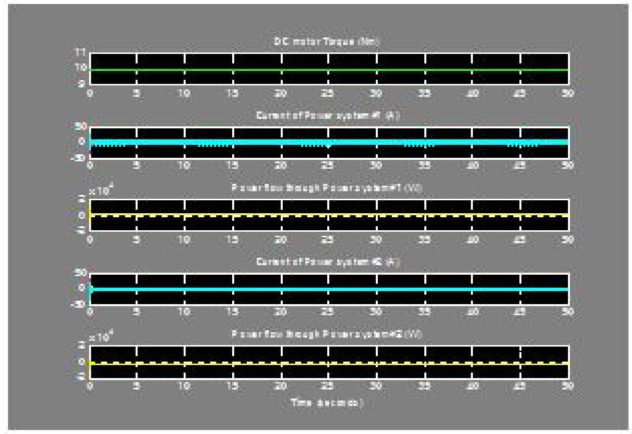

Figure 9. Waveforms showing torque, currents and power transfer

d) For $T_D = 15$ Nm, Fig.10 shows the waveforms.

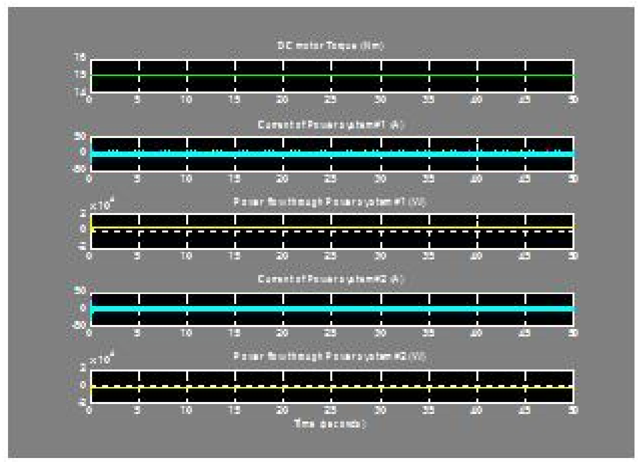

Figure 10. Waveforms showing torque, currents and power transfer

e) For $T_D = 20$ Nm, Fig.11shows the waveforms

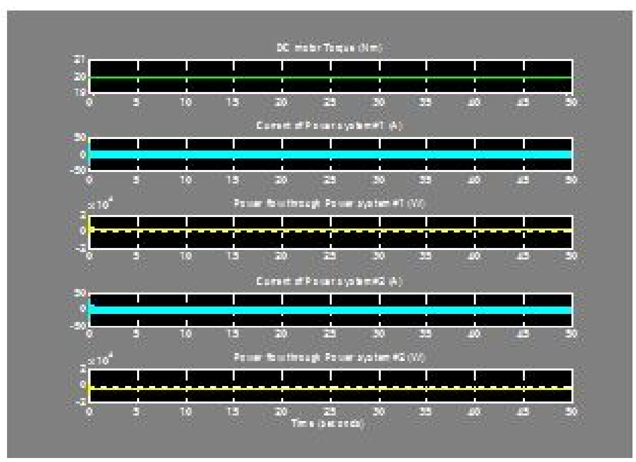

Figure 11. Waveforms showing torque, currents and power transfer

It is clear from table II as the applied torque direction reverses the power transfer direction also reverses. The negative sign represents the power transfer inside the power system#1.

The power transfer through power system#1 and power system#2 with the applied torque achieved is shown in Fig. 16.

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TABLE I. MATLAB SIMULATION RESULTS FOR VFT

S. No	T_D (Nm)	I_S (A)	P_S (W)	I_R (A)	P_R (W)
1	0	6.813	214	3.338	36.65
2	5	5.401	1089	3.088	-781.9
3	10	4.635	2010	2.528	-1564
4	15	4.827	2967	3.096	-2304
5	20	5.871	3964	4.518	-3005

f) For T_D = - 5 Nm, Fig.12 shows the waveforms.

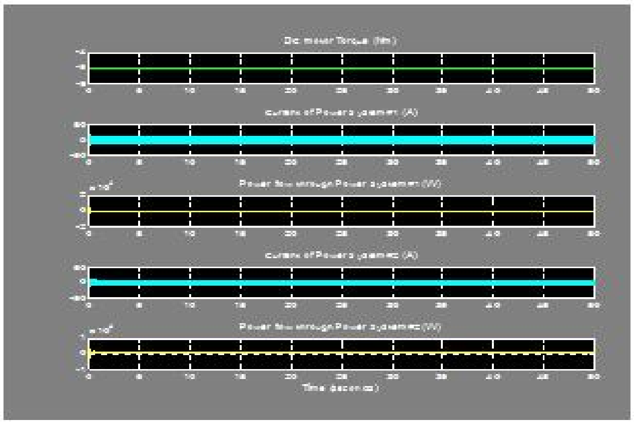

Figure 12. Waveforms showing torque, currents and power transfer

g) For T_D = - 10 Nm, Fig.13 shows the waveforms.

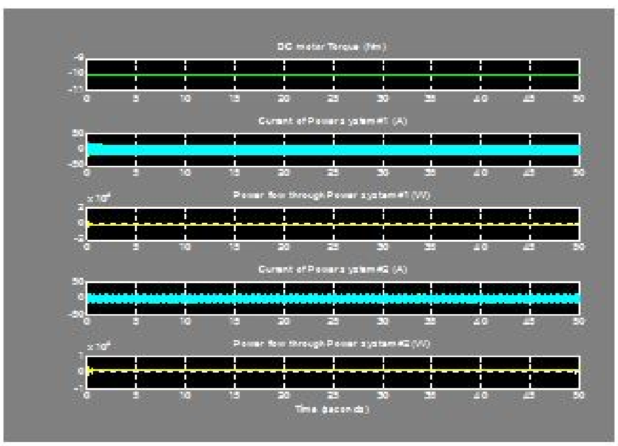

Figure 13. Waveforms showing torque, currents and power transfer

h) For T_D = - 15 Nm, Fig.14 shows the waveforms.

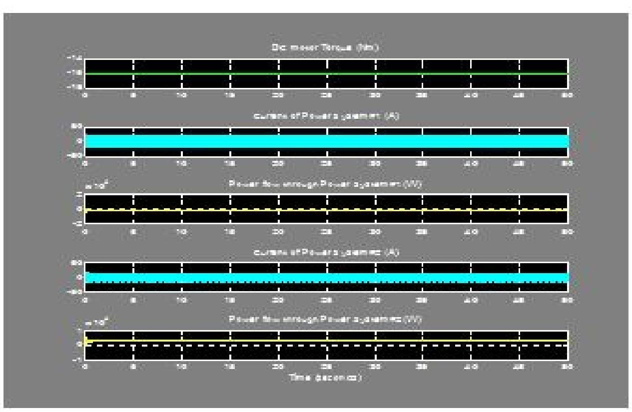

Figure 14. Waveforms showing torque, currents and power transfer

i) For T_D = - 20 Nm, Fig.15 shows the waveforms.

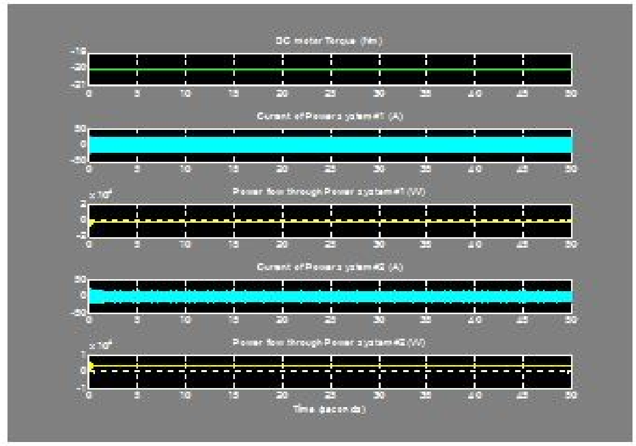

Figure 15. Waveforms showing torque, currents and power transfer

TABLE II. MATLAB SIMULATION RESULTS FOR VFT

S. No	T_D (Nm)	I_S (A)	P_S (W)	I_R (A)	P_R (W)
1	0	6.813	214	3.338	36.65
2	-5	8.587	-624.2	4.937	901
3	-10	10.57	-1416	6.829	1808
4	-15	12.68	-2162	8.882	2763
5	-20	14.91	-2583	11.07	3768

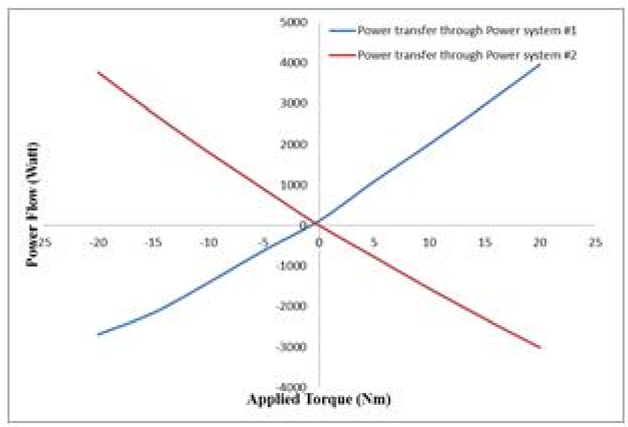

Figure 16. The power transfer with the applied torque

CONCLUSIONS

From the simulated result it is evident that power transfer is directly proportional to the external torque applied to the rotor. Moreover, both the magnitude and direction of the power transfer through the connected asynchronous power system networks are controllable by the torque. Hence, VFT technology is a viable technology for achieving real power transfer control between two or more asynchronous power system networks. The MATLAB Simulink model developed is successfully used to demonstrate the power transfer through asynchronous power system networks. The direction and the magnitude of power transfer control are achieved. The voltage, current, torque and power transfer plots are also obtained. Thus, the VFT concept discussed and its advantages are verified by simulation results. It has distinct advantages in terms of controllability over conventional

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phase angle regulating transformers and does not inherently produce harmonics as in case of many HVDC and FACTS technologies.

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BIOGRAPHY

Farhad Ilahi Bakhsh has received Diploma and B. Tech degree in Electrical Engineering from Aligarh Muslim University, Aligarh, India in 2006 and 2010 respectively. He was awarded University (Gold) Medal for standing first throughout Diploma In Engineering. Then he pursued Masters in Power System and Drives from the same university. Currently he is pursuing Ph.D. from Indian Institute of Technology, Roorkee. He is an IEEE Student member since 2011 and he also worked as head of R&D cell, IEEE student branch, AMU for around two years. He has published more than ten papers in International Journals, International Conferences including IEEE conferences and National Conferences. Moreover, he has three published patents. His research area of interests includes Power Systems, Power Electronics, Drives and Renewable Energy Systems.

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